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CERTIFICATE

This certificate is issued in support of an application for Patent registration in a country outside New Zealand pursuant to the Patents Act 1953 and the Regulations thereunder.

I hereby certify that annexed is a true copy of the Provisional Specification as filed on 27 November 2003 with an application for Letters Patent number 529869 made by AUCKLAND UNISERVICES LIMITED.

Dated 9 June 2004.

Neville Harris

Neville Harris
Commissioner of Patents, Trade Marks and Designs

COMMISSIONER OF PATENTS, TRADEMARKS & DESIGNS
NEW ZEALAND

529869

Patents Form No. 4

Our Ref: WEJ504669

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PROVISIONAL SPECIFICATION

METHODS & APPARATUS FOR CONTROL OF INDUCTIVELY COUPLED POWER TRANSFER SYSTEMS

We, **AUCKLAND UNISERVICES LIMITED,** a New Zealand company, of Level 10, 70 Symonds Street, Auckland 1001, New Zealand do hereby declare this invention to be described in the following statement:

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METHODS AND APPARATUS FOR CONTROL OF INDUCTIVELY COUPLED POWER TRANSFER SYSTEMS

FIELD OF THE INVENTION

This invention relates to Inductively Coupled Power Transfer (ICPT) systems and pick-ups for such systems.

BACKGROUND

ICPT power systems (also known as contactless power supplies) are known to have significant advantages in applications such as the materials handling, lighting and transportation industries. There are many applications in both high and low power systems in which use of these power supplies is advantageous.

ICPT systems have a primary conductive path supplied with current from a power supply. One or more secondary devices or pick-ups are provided adjacent to, but electrically isolated from, the primary path. The pick-ups have a pick-up coil in which a voltage is induced by the magnetic field associated with the primary path, and supply a load such as an electric motor, a light, or a sensor for example. The pick-up coil is usually tuned using a tuning capacitor to increase power transfer to the pick-up.

A problem with existing ICPT systems is control of the power transferred to pick-ups when they are lightly loaded, for example when a motor is supplied by a pick-up and is idle while it awaits a command from a control system. A solution to this control problem is the use of a shorting switch across the pick-up to decouple the pick-up when required and thus prevent flow of power from the primary path to the pick-up. This approach is described in US patent 5,293,308. However, although this addresses the control problem of lightly loaded pick-ups, the shorting switch causes large conduction losses at light loads because it is nearly always conducting in light load conditions.

Another problem with ICPT systems is variation in the frequency of the current in the primary path. Frequency drift can cause the primary path current to fluctuate which causes problems with control of power transferred to the pick-ups. More importantly, frequency drift can significantly affect the tuning of pick-ups, especially those that use fixed frequency tuning. This reduces the ability of the system to effectively transfer power.

Frequency drift can be caused by many factors. The most obvious is load change, but circuit parameter variations can also be significant.

OBJECT

It is an object of the present invention to provide a method of controlling, or apparatus for, an ICPT power supply which will ameliorate one or more of the disadvantages suffered by existing systems, or which will at least provide the public with a useful alternative.

SUMMARY OF THE INVENTION

Accordingly in one aspect the invention may broadly be said to provide an ICPT pick-up having a pick-up circuit including a capacitive element and an inductive element adapted to receive power from a magnetic field associated with a primary conductive path to supply a load, sensing means to sense a condition of the load, and control means to selectively tune or de-tune the pick-up in response to the sensing means by varying the effective capacitance or inductance of the pick-up circuit to control the transfer of power to the pick-up dependant on the sensed load condition.

Preferably the control means includes a variable capacitor.

Alternatively the control means includes a variable inductor.

Preferably the control means includes a capacitive or inductive element and a switching means.

Preferably the control means includes means to control the switching means so that the capacitive or inductive element varies the effective capacitance or inductance of the tuned circuit to thereby tune or detune the pick-up circuit.

Preferably the sensing means senses the power required by the load.

In a further aspect, the invention may broadly be said to provide an ICPT system having a power supply, a primary conductive path connected to the power supply, and one or more pick-ups according to one or more of the preceding paragraphs to supply power to one or more loads.

In a further aspect the invention may broadly be said to provide an ICPT power supply having a tank circuit including an inductive element and a capacitive element, an output for connection to a primary conductive path of an ICPT system, frequency detection means to detect the frequency of output current supplied to output, and control means to selectively tune or de-tune the tank circuit in response to the frequency detection means by varying the effective capacitance or inductance of the tank circuit to maintain the frequency of the output current substantially constant.

Preferably the control means includes a variable capacitor.

Alternatively the control means includes a variable inductor.

Preferably the control means includes a capacitive or inductive element and a switching means.

Preferably the control means includes means to control the switching means so that the capacitive or inductive element varies the effective capacitance or inductance of the tank circuit to thereby tune or detune the tank circuit to alter the output frequency.

In a further aspect, the invention may broadly be said to provide an ICPT system having a power supply according to the preceding statement of invention, a primary conductive path connected to the power supply, and one or more pick-ups.

In a further aspect the invention may broadly be said to consist in a method for controlling power drawn by an ICPT pick-up, the method including the steps of sensing a load condition of the pick-up, and selectively tuning or detuning the pick-up circuit depending upon the sensed load condition.

Preferably the step of tuning or detuning the pickup circuit includes moving the resonant frequency of the pick-up circuit toward or away from a tuned condition.

Preferably the step of tuning or detuning the pick-up circuit includes the step of controlling a variable capacitor or inductor.

Preferably the step of controlling the variable capacitor or inductor includes the step of switching the capacitor or inductor into or out of the pick-up circuit to tune or detune the pick-up circuit.

In a further aspect the invention may broadly be said to consist in a method for controlling the frequency of current provided by an ICPT primary power supply having a supply tank circuit, the method including the steps of detecting an output frequency of the supply, and selectively tuning or detuning the supply tank circuit depending upon the detected frequency to maintain the frequency substantially constant.

Preferably the step of tuning or detuning the tank circuit includes moving the resonant frequency of the tank circuit toward or away from a tuned condition.

Preferably the step of tuning or detuning the tank circuit includes the step of controlling a variable capacitor or inductor.

Preferably the step of controlling the variable capacitor or inductor includes the step of switching the capacitor or inductor into or out of the tank circuit to tune or detune the tuned circuit.

The invention may also broadly be said to consist in any new part feature or element disclosed herein, or any new combination of such parts, features or elements.

For the purposes of this specification, the word "comprise" and variations such as "comprises" or "comprising" is to be interpreted in an inclusive sense unless the context clearly dictates the contrary.

DRAWING DESCRIPTION

One or more examples of an embodiment of the invention will be described below with reference to the accompanying drawing in which:

Figure 1 is a diagram of the basic structure of a known ICPT system,

Figure 2 is a diagram of a pick-up circuit topology including a variable inductor for an ICPT power supply,

Figure 3 is a diagram of a pick-up circuit topology including a variable capacitor for

an ICPT power supply,

Figure 4 is a simplified circuit diagram of the circuit of Figure 3,

Figure 5 is a graph of equivalent capacitance against Q factor for the circuit of Figure 4,

Figure 6 is a circuit diagram of a known form of primary power supply, and

Figure 7 is a circuit diagram of a primary power supply including a variable capacitor.

DETAILED DESCRIPTION

Referring to Figure 1, the basic structure of an ICPT power supply (also known as a contactless power supply) system is shown. The system generally comprises two electrically isolated parts. The first part consists of a power supply such as a resonant converter (2) which has inputs (4) for connection to a source of electrical energy, in this example the inputs (4) may be connected to a 50 Hertz mains supply. The first part also includes a primary conductive path (6) which is supplied with alternating current from the resonant converter (2). The primary conductive path (6) is usually in the form of an elongated "track" along which one or more of the second parts are located. In this example, the main function of the converter is to supply a nominally constant high frequency AC current of about 20 amps rms at 40 kHz with a sinusoidal waveform in the track loop.

The second part consists of one or more pick-ups (8), each of which includes a pick-up conductive element which is usually in the form of a coil (10). The pick-up also includes a controller (12) to control the transfer of power from the track loop to the pick-up. The power is supplied to a load (14). In this example the controller (12) comprises a microcomputer to control the pick-up circuit in accordance with the invention, as will be described further below. Also, in this example, the load (14) comprises a sensor such as a fast moving sensor. One example of such a sensor is a camera which may be required to travel the length of the track loop (6) rapidly in order to provide information for implementation of a control system or process in an industrial environment.

Due to the mutual magnetic coupling between the primary conductive path (6) and the secondary pick-up coil (10), an electromotive force is induced in the pick-up coil (10). This voltage then becomes the source for the secondary power supply. Since then magnetic coupling is very loose compared to normal closely coupled transformers, the induced

voltage is usually unsuitable for direct use. As such, a control mechanism is necessary to regulate the power in the form required by the load (14). In the fast moving sensor example discussed with reference to Figure 1, the output of the pick-up required by the sensor is normally 24 volts DC.

An example of a pick-up topology which includes a variable inductor is shown in Figure 2. The topology in Figure 2 is a parallel tuned pick-up i.e. the tuning capacitor (22) is connected in parallel with the pick-up coil (10). The variable inductor (40) is also connected in parallel with the pick-up coil and the tuning capacitor. Alternatively, the pick-up coil could be used in accordance with the invention to provide the variable inductance.

In Figure 2, the detuning element comprises an inductance (40) with two switches (42) and (44) with appropriate drivers (not shown) to control the voltage or current flowing through the reactive component.

We have found that we can use fast semiconductor switches such as MOSFETs and IGBTs to control an inductor in such a manner that a variable inductance is provided in the pick-up circuit. Fast switches are necessary with the high frequencies (10 – 100 KHZ) used in ICPT power systems. However these switches are DC switches having only unidirectional current flow control. To accommodate alternating currents, two such DC switches may be used represented by switches (42) and (44) in Figure 2.

Each of the switches (42) and (44) has associated anti-parallel diodes (46) and (48) respectively, which allow the alternating inductor current to flow in both directions. Thus the inductor (40) can be controlled to selectively tune or detune the circuit dependant on the magnitude of the load. Under normal loading conditions the inductor can be switched "off" so that the pick-up circuit is tuned back again to transfer the required power.

The switches (42) and (44) are controlled dependant on the current in the pick-up resonant circuit such that the inductor (40) is phase controlled. The switches (42) and (44) are initially controlled by both being turned on. This allows the inductor current to increase gradually in one direction, depending on the direction of the applied voltage. Therefore, zero current switching (ZCS) turning on is essentially achieved. In order to achieve zero current switching when turning off, the inductor current is detected by

detection means (not shown) and a switch is only turned "off" when its anti-parallel diode is conducting. In this way, each switch (42) or (44) is not only switched at zero current but also at approximately zero voltage conditions (only the diode voltage drop of about one volt). Therefore the switching losses are significantly reduced and the conduction losses introduced in the phase controlled inductor are negligible.

Therefore, the tuning capacitor Cs is chosen to provide a pick-up tuned to a particular supply frequency for the primary conductive path. The equivalent inductance of the phase controlled inductor (40) can be controlled by switches (42) and (44) to increase or decrease the overall or effective inductance of the tuned pick-up circuit, and thus vary the resonant frequency of the circuit. In this way, the pick-up can be detuned away from resonance (i.e. the track frequency) as sensing means (not shown) sense the load reduces to thereby reduce the transfer of power to the pick-up. Similarly, the pick-up can be tuned toward the track frequency as the load is sensed to increase to thereby increase the transfer of power to the pick-up to satisfy the demand from the increased load.

We have found an adequate range of control may be achieved with a phase controlled inductor (40) using an inductor that is approximately five times the magnitude of the inductance of the pick-up coil (10).

This control strategy may be implemented in such a way that the pick-up is tuned or detuned simply dependant on the load (for example by monitoring the output voltage Vo). Thus the pick-up can be tuned or detuned toward or away from the frequency that the track is operating at. This means that the frequency of the current in the primary path is not as critical for adequate performance as it is with known systems. Whatever the track frequency happens to be, the present invention can tune to that frequency if required to obtain maximum power transfer to the pick-up.

A further advantage with the invention is that the shorting switch and diode of known pick-up circuit topologies are not required.

Rather than using a variable inductance, a variable capacitance may be used as shown in Figure 3. Referring to that Figure, circuit elements that are the same as or similar to those described above are labelled using the same reference numerals. As can be seen, the difference with respect to Figure 2 is the use of a variable capacitance (50) rather than a variable inductance. Although not shown in Figure 3, the variable capacitance preferably

comprises a capacitor connected across capacitor (22) via two switching elements such as the FETs (42) and (44) shown in Figure 2. Therefore, the switches may be controlled to control the equivalent capacitance of the variable capacitor, and thus tune or detune the pick-up as described above in relation to Figure 2. Again, the tuning capacitor (22) may be used alone to provide the variable capacitor.

If a circuit in which a variable capacitance is arranged in parallel with the tuning capacitor (22) is used (such as the topology shown in Figure 3), then capacitor (22) may be selected to be approximately one half of the capacitance required to provide resonance at the intended primary current frequency. The variable capacitor may also comprise a capacitor of the same magnitude (i.e. one half of the capacitance required to provide resonance at the intended primary current frequency). This allows an adequate range of capacitance to be provided to allow reasonable control.

A simplified equivalent circuit to that shown in Figure 3 is set forth in Figure 4 and may be used to assist with the follow theoretical analysis.

Ideally for a simplified model as shown in Figure 4, to maintain the output voltage Vo constant without shorting the shunt switch S in the steady state, the capacitance should be detuned according to:

$$C_{eq} = C_s\left(1 - \frac{1}{Q}\sqrt{(Q/k)^2 - 1}\right) \qquad (1)$$

Where Cs is the original tuning capacitance (22), Q $(=R/\omega L_s)$ is the quality factor which reflects the load change, and k is the actual required boost up factor from the open circuit voltage V_{OC} to the output voltage Vo, ie, $k=V_o/V_{oc}$.

From Eqn (4) the relationship between the load change (in terms of Q) and tuning capacitor (with respect to the original tuning capacitor) is calculated and shown in Figure 5.

From Figure 5 it can be seen that under detuned condition, Q must be larger than k in order to keep the output voltage constant. If there is no load, Q would be infinity. To keep k (thus the output voltage Vo) constant against the load change, Ceq is tuned dynamically. The minimum capacitor is determined by:

$$C_{eq} = \lim_{Q\to\infty} C_s\left(1-\frac{1}{Q}\sqrt{(Q/k)^2-1}\right) = C_s(1-1/k) \qquad (2)$$

It is clear that the larger the voltage boost factor k needed, the smaller the capacitor tuning ratio that is required. This is because the circuit becomes more sensitive to the load change when the boosting factor is high. Such a property is desirable for minimising the power pick-up size as the open circuit voltage can be lower.

As mentioned above, it is desirable to maintain the frequency of the current on the primary path substantially constant. We have found that a variable inductance or capacitance may be used to achieve frequency stability. Instead of monitoring the output power of the pick-up, we can monitor the frequency of the primary supply and control it to be constant. The switching methods described above, or similar methods, may be used to control the switching of the variable capacitors or inductors described in this document.

Figure 6 shows the basic structure of a known push/pull current fed parallel resonant converter used to supply current to the primary path. It consists of a capacitor (C) in parallel with an inductor (L) and a series load (R) which can be the equivalent resistor referred back from the secondary power pick-up circuits. A DC inductor (Ld) smoothes the input current and the splitting transformer (K), together with switch devices S1 and S2 (for example IGBTs) allow the input DC current from the "current source" to be divided into two directions so that the injected AC current into the resonant tank becomes half of the DC current. This occurs because the inductance of the splitting transformer windings (Lsp) is very large compared to the inductance of the resonant inductor (L).

We have found that the inductor (L) or the capacitor (C) of Figure 6 may be replaced by (or augmented by) a controlled variable inductance or capacitance. The application of our variable capacitor design is shown in a power supply in Figure 7. As shown in that figure, the controlled variable capacitor (60) may be placed in parallel with the resonant capacitor. The variable capacitor includes capacitor (62) and switches (64) and (66) which may be controlled to allow selected conduction of the capacitor (62) to thus vary the effective capacitance of the tank circuit. Because the original tuning capacitor and the new variable capacitor are in parallel, zero voltage switching techniques are preferably used to ensure smooth transients, as well as minimise the power losses and EMI.

Detection means (not shown) detect the current output by the supply shown in Figure 7, and this information is used by control means (not shown) to control switches (64) and

(66) to vary the effective capacitance and thus the frequency of the tank circuit. In this way the output frequency may be controlled to be substantially constant.

A dynamic power control circuit for contactless power supply applications has been proposed. This has been achieved by introducing a variable switched capacitor or inductor into the primary or secondary resonant circuits of ICPT power supplies.

The invention allows a number of approaches to be adopted to provide an improved ICPT supply system since pick-ups according to the invention may be used in conjunction with a known (poor frequency regulated) primary supply, or a primary supply according to the invention may be used with known pick-up topologies, or both a supply and pick-ups according to the invention may be used to provide an improved system.

There are a wide variety of applications for the invention including delivery of electrical energy to a variety of loads, including sensors, in environments where traditional conductive paths are undesirable. Examples include production facilities in clean room environments, moving apparatus such as fast-moving sensors, battery charging or recharging, forestry, bio-implants, underwater and mining environments where traditional conductive elements are inconvenient or experience excessive wear.

As another example, the invention may be used to wirelessly power, charge or recharge desktop equipment such as mobile computing devices and mobile communication devices. A primary conductive path according to the invention can be provided in a mouse pad or in or under a desk top or work surface. A pick-up according to the invention may be provided in a mouse, mobile phone or laptop computer so that the pick-up can be used to transfer power to the device for operation of the device and/or for charging a battery in the device. A problem with placing the primary conductive path in an environment where it may be used to charge multiple devices (e.g. a mouse and a mobile telephone and perhaps also a computer) is that the load may vary considerably dependent on how many devices are powered and how close they are to the conductive path. Extraneous load factors such as the placement of nearby metal objects may also create significant load variations. The present invention overcomes these problems by allowing a stable supply current frequency and/or a tuned pick-up to be provided which can compensate for load variations to allow required performance to be achieved.

One particular example of an application of the invention is in the marine industry for

which the invention can allow sensors or other electrical loads on a marine vessel, for example, to be reliably supplied with electrical energy despite the adverse environment. Thus, rather than drilling holes through the hull of a vessel to provide power to depth sensors or "fish-finder" sensors, a primary conductive path may be provided within the hull and pick-ups provided in the sensors externally of the hull can supply the sensors. The primary path may be provided throughout the vessel and may even be provided as an integral part of the vessel during manufacture of the hull/superstructure. In this way a very wide variety of loads can be supplied, such as navigation lights, instrumentation and other transducers such as sensors or entertainment systems.

Wherein the foregoing description reference has been made to specific components or integers of the invention having known equivalents then such equivalents are herein incorporated as if individually set forth.

Although the invention has been described by way of example and with reference to possible embodiments thereof, it is to be understood that modifications or improvements may be made thereto without departing from the scope of the invention.

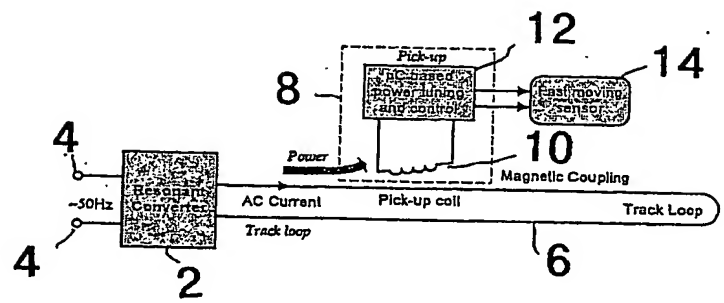

FIGURE 1

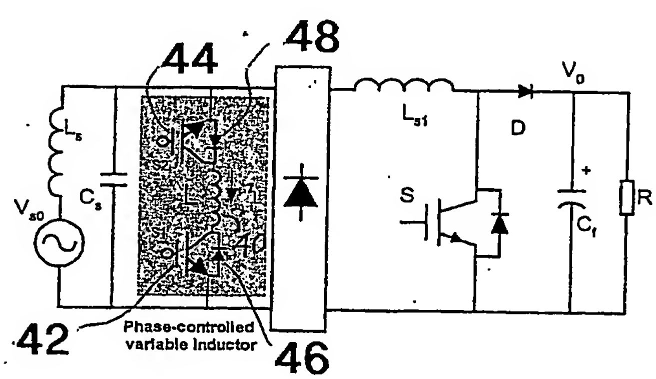

FIGURE 2

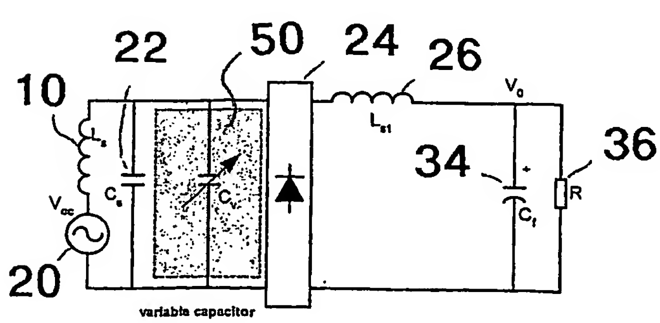

FIGURE 3

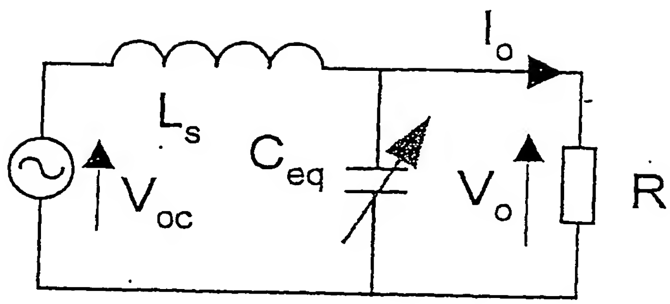

FIGURE 4

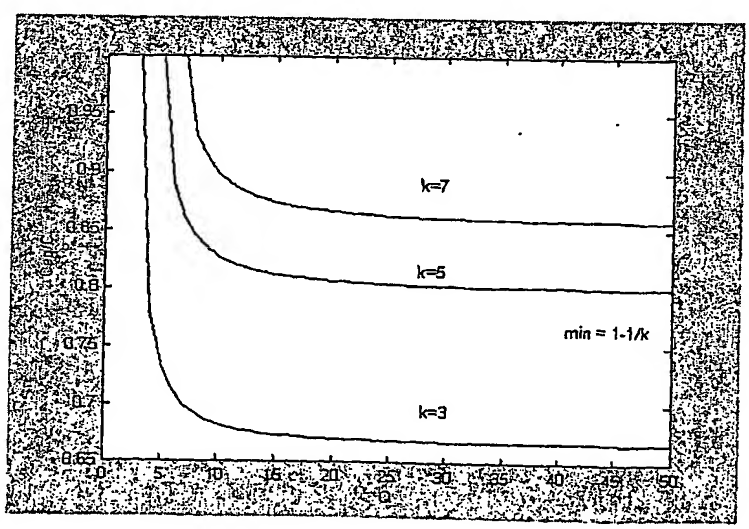

FIGURE 5

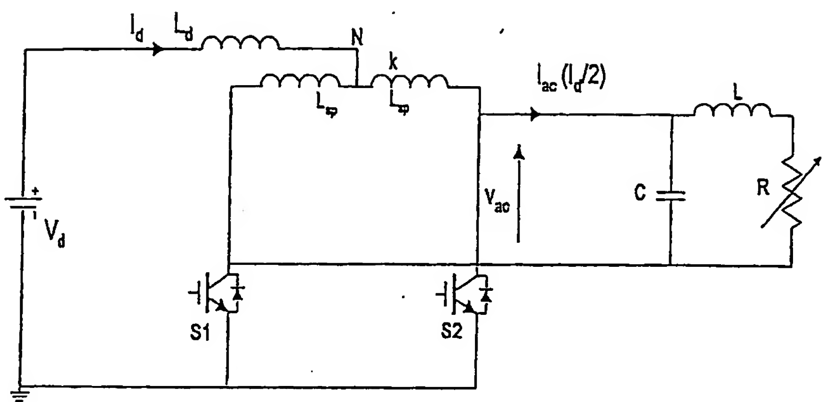

FIGURE 6

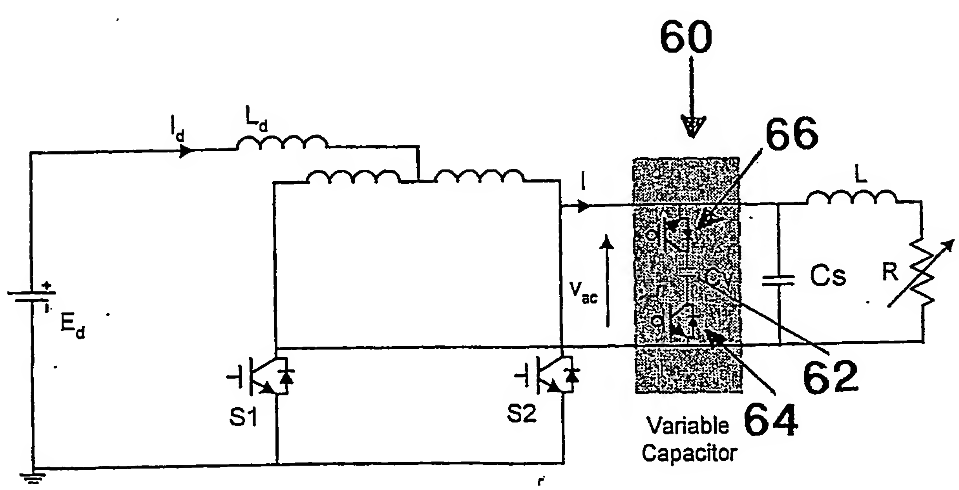

FIGURE 7